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IX.—*Account of Experiments made on a New Friction Sledge for stopping Railway Trains.* By the Rev. SAMUEL HAUGHTON, Fellow of Trinity College, Dublin.

Read June 4, 1850.

THE instrument which is here described, and with which the following experiments were made, is the invention of Mr. S. WILFRED HAUGHTON, Engineer, and Superintendent of the Dublin and Kingstown Railway Engine Factory at Ringsend Docks. It is intended to be used at the termini of railways, instead of the spring buffer usually employed to stop the train, in case it should happen, through the carelessness of the engine-driver or guards, to enter the terminus with too great speed. The objection to the use of the spring-buffer is twofold: the space through which the recoil can take place is too short, and the second recoil of the spring produces effects which are only less dangerous than those of the first shock; this latter inconvenience is sometimes remedied by the use of ratchets, which prevent the recoil of the spring after it has been compressed by the shock. But the first objection is founded on the use of the spring itself, and cannot be removed. A careful consideration of these objections led Mr. S. W. HAUGHTON to the invention of his Friction Sledge, as a substitute for the spring buffer.

The Friction Sledge consists of two strong wooden frames, shod with iron, and shaped as in the annexed diagram, which represents a side view of the sledge in action; these two frames are provided with iron flanges on the inside (so as to prevent them from slipping off the rails), and being placed parallel to each other at a distance equal to the interval between the rails, are strongly tied together by iron braces. The sledge, being placed upon the rails, is ready to perform its office of stopping a train moving with any moderate degree of velocity. The engine or foremost carriage of the train runs forward upon the sledge, and, striking against its curved front, receives a shock, which, if the sledge were immoveable, would be as fatal as the shock caused by impinging upon a stone wall; but the sledge, having sustained a portion of the shock, slides forward, and the remainder of the momentum is gradually destroyed by its friction against the rails.

The first time I had an opportunity of seeing the Friction Sledge in action was upon the 20th of April, 1849, on which occasion no accurate record was kept of its performance; it appeared, however, so completely successful in a practical point of view, that I was induced to attempt a few experiments, with a view of obtaining a correct knowledge, theoretical and practical, of its mode of action. I take this opportunity of acknowledging the kindness of the Board of Directors of the Dublin and Kingstown Railway, in allowing the use of waggons and a portion of the rails suited to the experiments; and of stating the obligations I am under to Mr. Wilfred Haughton and the Rev. Joseph A. Galbraith, without whose assistance in conducting the experiments, and afterwards in calculating their results, I should have been unable to complete this account.

Our first experiments were performed on the 27th of April, 1849, with an engine and train of five empty passenger carriages,* in the presence of the Rev. T. Romney Robinson, D.D., of Armagh Observatory, and Mr. Bergin, Secretary to the Dublin and Kingstown Railway. On this occasion our mode of measuring the velocity of the train was so imperfect, that I shall merely state the general results, without attempting to deduce any accurate conclusions from them.

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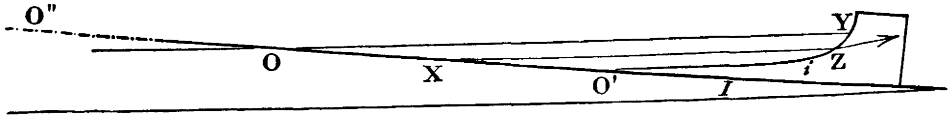
* The velocity of the train on this occasion was determined by counting with a chronograph the time occupied in performing the last four or five revolutions of the driving wheels of the engine; this determination, however, was rendered uncertain by the occasional slipping of the wheels on the damp rails.

Number of Experiment.	Velocity of Impact.	Length of Slide.
1	8·6 miles per hour.	13·66 feet.
2	9·4 „ „	14·75 „
3	8·2 „ „	12·58 „
4	9·4 „ „	16·33 „
5	9·0 „ „	15·50 „
6	10·5 „ „	18·16 „

The weight of the engine and train was about 32 tons, and the sledge 7 cwt. The results of this trial are sufficient to prove the great efficiency of the Friction Sledge as a means of stopping a train in motion.

In order to obtain more accurate results, I determined to experiment with a single loaded waggon; and to measure the velocity with precision, I used a portion of the rails inclined to the horizon, and measured, by means of a pair of chronographs reading to the fifth of a second, the time of describing a given space, when the waggon was made to enter upon the inclined plane with an unknown velocity; or measured the space traversed by the waggon, when its whole motion took place on the inclined plane.

The subsequent experiments on the Friction Sledge were conducted as follows:—An inclined plane of about 160 feet, on the rails at the Engine Factory, Ringsend Docks, was selected, at the lower extremity of which the friction sledge was placed, and a loaded waggon was either pushed or allowed to run down the inclined plane, so as to impinge upon the sledge at the bottom. The velocity of impact and the length of the slide were the quantities to be measured, from which all others could be inferred by calculation ; the velocity of impact was measured by noting the time taken by the loaded waggon to pass over a measured space on the inclined plane, or by allowing the waggon to start from fixed points on the inclined plane.



Let O″OO′ be a portion of the inclined plane, *I* the inclination of the plane to the horizon, i the angle which the axis of the waggon makes with the inclined plane when the front wheel is at the point Z. The line OY is horizontal; X is the point of bisection of OO′; and XZ is also horizontal. The velocity of the waggon at O′ is its velocity at the commencement of the shock; the velocity at O is equal (neglecting the friction of the wheels) to its velocity at Y; i. e., its velocity at the end of the shock.

I shall assume that the shock consists of a single blow given at the point Z with the velocity which animates the waggon at the point X.

If v' represent this velocity, then the velocity of impact actually imparted to the sledge will be

$$v = \frac{mv'}{m + m'},$$

m denoting the weight of the waggon,
m' . . . . sledge.

If V represent the velocity with which the sledge and waggon begin to move, and μ, k, represent the coefficients of friction of rest and motion respectively, we easily obtain (*neglecting the loss of momentum caused by imperfect elasticity*) the following equations:

$$V = v \cos i - \mu (g \cos I - v \sin i); \qquad (1)$$

$$V^2 = 2gs \, (k \cos I - \sin I); \qquad (2)$$

the first of which expresses the fact, that the momentum with which the sledge begins to move is equal to the difference between the original momentum and that destroyed by the friction of rest; the second equation is true on the hypothesis, that the friction of motion is a constant retarding force; eliminating V between these equations we obtain

$$v = A \sqrt{s} + \mu u \sec i; \qquad (3)$$

A and u being defined by the following equations:

$$A \cos i = \sqrt{(2g \, [k \cos I - \sin I])},$$

$$u = g \cos I - v \sin i.$$

Each experiment tried with the Friction Sledge, should give particular values for s and v; which, substituted in (3), would afford a relation between

A and μ. A few trials soon convinced me that μ was not a constant, and that equation (3) did not represent the experiments ; this result might have been foreseen, as the loss of motion arising from the shock of imperfectly elastic bodies was neglected in finding equation (3). I could not discover any direct method of introducing the loss of motion due to the shock, and therefore sought to modify equation (3) by experiment, so as to make it represent what actually occurred in each trial. After many failures I was induced to assume

$$\mu = Kv,$$

K being a constant. Introducing this value of μ into (3), and dividing by $\sqrt{s}$, we obtain

$$\frac{v}{\sqrt{s}} = A + K \sec i \frac{uv}{\sqrt{s}}. \qquad (4)$$

I hope to be able to show that this equation represents faithfully the whole series of experiments, and that, too, with a degree of accuracy which seems to prove that it is the true expression of the facts which were observed.

The numerical values of the constants in the above equations were determined with care, and are as follows :

$$\text{OO}' = 22{\cdot}5 \text{ feet}, \quad \sin I = {\cdot}0146, \quad \sin i = {\cdot}050\,;$$
$$\text{O}'\text{X} = 11{\cdot}25 \text{ feet}, \quad \cos I = {\cdot}999, \quad \cos i = {\cdot}998.$$

The force down the inclined plane, allowing 10lbs. per ton for friction, resistance of air, &c., is consequently,

$$f = {\cdot}4651 \text{ ft.}$$

The original measurements and calculated results are all given in the following tables, in which I have not suppressed a single experiment, although one of them is undoubtedly erroneous. The evidence on which I was induced to adopt the form (4) is completely given, and an opportunity thus offered for another interpretation of the experiments, although the accuracy with which equation (4) represents the results seems to preclude the possibility of an interpretation differing much from that which is here given.

FIRST SERIES.

January 25, 1850.—*Day damp and wet.*

cwt. qrs. lbs.
Weight of waggon = 99 0 0.
Weight of sledge, = 4 3 21.

TABLE (1).—ORIGINAL MEASUREMENTS.

No.	Time.	Slide.		Observations.
	Secs.	Ft.	In.	
1	9·2	7	6	
2	17·0	4	$1\frac{1}{2}$	First explosion off hind wheel. Interval between wheels, 7ft. 6in.
3	10·4	6	$6\frac{1}{4}$	
4	9·2	7	0	
5	11·2	5	4	
6	11·0	5	$7\frac{1}{4}$	Explosion off hind wheel.
7	10·2	5	8	
8	9·4	6	9	

The first and second of these experiments were performed by placing two fog signals on the rails at O and O″, distant from each other 100 feet, and measuring with a chronograph the interval of time between the explosions, as registered in the first column; the remaining experiments were performed with one fog signal placed at O, the time of the front wheel passing O″ being observed by sight. The waggon was impelled by a number of men, who ceased pushing it before its arrival at O″.

TABLE (2).—CALCULATED RESULTS.

No.	v'.	$\sqrt{s}$.	v.	u.	$\frac{v}{\sqrt{s}}$	$\frac{uv}{\sqrt{s}}$
1	13·413	2·738	12·775	31·496	4·6658	146·954
2	9·947	2·031	9·474	31·661	4·6647	147·689
3	12·470	2·553	11·877	31·541	4·6521	146·734
4	13·413	2·645	12·775	31·496	4·8298	152·121
5	11·987	2·309	11·417	31·564	4·9445	156·070
6	12·479	2·367	11·886	31·540	5·0215	158·379
7	12·607	2·380	12·008	31·534	5·0453	159·101
8	13·234	2·598	12·605	31·504	4·8518	152·851

In this Table v' denotes the velocity of the waggon at the point X, situated 11 feet above the sledge; i. e. it is the mean of the initial and final velocities of the shock; it is computed from the velocity at O, by adding to its square the square of the velocity due to the space OX, and extracting the square root of the sum. The velocity at O is found from the formula

$$v'' = \frac{200 + \cdot 4651\, t^2}{2t},$$

in which t denotes the time of describing OO″, in Table (1). In Exp. (2) we must substitute 185 for 200 in the formula; and in Exp. (6), 215 instead of 200, adding, in the latter case, in order to compute v', the square of the velocity due to 4 feet instead of 11·25 feet.

In the second column, $\sqrt{s}$ is found from the second column of Table (1).

In the third column, $v = \cdot 9525\, v'$; the numerical coefficient being deduced from the weights of the waggon and sledge.

In the fourth column, $u = 32{\cdot}134 - {\cdot}05\, v$; the coefficients being deduced from the equation which defines u (p. 222).

SECOND SERIES.

January 26, 1850.—*Wet day.*

Weights of waggon and sledge same as before.

TABLE (1).—ORIGINAL MEASUREMENTS.

No.	Time.	Slide.		Observations.
	Secs.	Ft.	In.	
1	11·0	6	3½	
2	11·8	6	3¾	
3	13·6	5	6⅛	
4	17·2	4	2	
5	19·0	3	11½	Explosion off hind wheel.
6	17·4	3	11¼	
7	17·8	3	4⅛	
8	17·4	3	2⅝	
9	18·4	3	1⅛	
10	8·8	9	0⅞	
11	8·4	11	6¾	
12	8·4	10	9	

These experiments were tried in a manner similar to the last six experiments of the first series.

TABLE (2).—CALCULATED RESULTS.

No.	v'.	$\surd s$.	v.	u.	$\frac{v}{\surd s}$	$\frac{uv}{\surd s}$
1	12·112	2·508	11·536	31·558	4·5996	145·157
2	11·685	2·512	11·130	31·578	4·4307	139·914
3	11·012	2·347	10·489	31·610	4·4691	141·268
4	10·344	2·041	9·852	31·641	4·8270	152·733
5	10·256	1·989	9·769	31·646	4·9115	155·430
6	10·325	1·984	9·834	31·643	4·9566	156·843
7	10·290	1·828	9·801	31·644	5·3616	169·662
8	10·325	1·794	9.834	31·643	5·4816	173·454
9	10·249	1·758	9.762	31·646	5·5529	175·727
10	13·803	3·012	13·147	31·477	4·3648	137·393
11	14·238	3·400	13·561	31·456	3·9885	125·463
12	14·238	3·278	13·561	31·456	4·1370	130·132

The quantities here tabulated are the same as in the first series of experiments; and in calculating v' for Exp. 5, the same method was followed as in Exp. 6 of first series.

THIRD SERIES.

February 23, 1850.—*Fine day.*

Weights of waggon and sledge same as before.

The mode of estimating the velocity on this day was to allow the waggon to run down the inclined plane a measured distance, and thence compute the velocity of the impact.

TABLE (1).—ORIGINAL MEASUREMENTS.

No.		OO″.	Slide.		No.		OO′.	Slide.
		Ft.	In.				Ft.	In.
I.	1	25	8·80		III.	1	75	32·45
	2	”	9·40			2	”	33·80
	3	”	10·60			3	”	33·15
	4	”	11·25		IV.	1	100	44·70
	5	”	11·25			2	”	46·00
II.	1	50	22·50			3	”	46·75
	2	”	22·85			4	”	47·60
	3	”	23·10			5	”	47·50
	4	”	22·60					

Table (2).—Calculated Results.

No.	v'.	$\sqrt{s}$.	v.	u.	$\frac{v}{\sqrt{s}}$	$\frac{uv}{\sqrt{s}}$
I.	5·827	·924	5·550	31·857	6·0065	191·349
II.	7·563	1·377	7·203	31·774	5·2309	166·208
III.	8·970	1·661	8·544	31·707	5·1439	163·097
IV.	10·184	1·968	9·700	31·649	4·9288	155·994

The velocity v' at the point X is found from the formula

$$v'^2 = 2fs = \cdot 9302\, s,$$

s denoting OO″; and from v' and s the remaining quantities are calculated as before.

Fourth Series.

March 5, 1850.—*Fine day.*

	tons.	cwts.	qrs.	lbs.
Weight of waggon =	2	4	3	8.
Weight of sledge =		4	3	21.

The velocity of impact was determined as in third series.

Table (1).—Original Measurements.

No.		OO″.	Slide.
		Ft.	In.
I.	1	25	5·6
	2	”	6·025
	3	”	5·75
	4	”	5·55
II.	1	50	14·6
	2	”	15·2
	3	”	15·35
	4	”	15·7
III.	1	75	23·1
	2	”	23·75
	3	”	24·0
IV.	1	100	32·5
	2	”	27·2
	3	”	30·1
	4	”	28·75

Note.—The point O in these experiments is 20 feet above the sledge.

TABLE (2).—CALCULATED RESULTS.

No.	v'.	$\sqrt{s}$.	v.	u.	$\frac{v}{\sqrt{s}}$	$\frac{uv}{\sqrt{s}}$
I.	5·623	·692	5·061	31·881	7·3136	233·164
II.	7·408	1·125	6·668	31·801	5·9244	188·488
III.	8·839	1·407	7·955	31·737	5·6538	179·437
IV.	10·069	1·571	9·062	31·681	5·7683	182·746

In this Table v is calculated by the formula

$$v = \cdot 9v';$$

the other quantities are deduced in the same manner as in the other experiments.

Having obtained the results calculated from the foregoing series of experiments, I had recourse to equation (4),

$$\frac{v}{\sqrt{s}} = A + K \sec i \, \frac{uv}{\sqrt{s}},$$

which contains two unknown quantities, A and K sec i. Having found approximate values of these quantities in each of the four series of experiments, I then, by trial of successive numbers extending to the fourth decimal place, obtained finally the following results, which give the values of K sec i and A which best satisfy all the experiments.

FIRST SERIES.

K sec i = ·0313.	A =	1°	·0662
		2°	·0420
		3°	·0594
		4°	·0685
		5°	·0596
		6°	·0643
		7°	·0655
		8°	·0675
		Mean =	·0644

Rejecting the second experiment, which is manifestly erroneous.

SECOND SERIES.

K sec i = ·0311.	A =	1°	·0843	7°	·0851
		2°	·0794	8°	·0873
		3°	·0757	9°	·0879
		4°	·0771	10°	·0920
		5°	·0777	11°	·0867
		6°	·0788	12°	0900
					Mean = ·0835

THIRD SERIES.

K sec i = ·0305.	A =	1°	·1704
		2°	·1616
		3°	·1695
		4°	·1710
			Mean = ·1681

FOURTH SERIES.

K sec i = ·0307.	A =	1°	·1555
		2°	·1379
		3°	·1451
		4°	·1580
			Mean = ·1491

Referring to p. 222, we find

$$A \cos i = \surd\{2g(k \cos I - \sin I)\}.$$

Hence,

$$\frac{(A \cos i)^2}{2g} + \sin I = k \cos I;$$

or,

$$k = \cdot 0154\, A^2 + \cdot 0146.$$

Computing the four values of k from this formula, we obtain finally, for the two coefficients,

$$\begin{array}{ll} (1)\ K = {\cdot}0313 & (1)\ k = {\cdot}0147 \\ (2)\ K = {\cdot}0311 & (2)\ k = {\cdot}0147 \\ (3)\ K = {\cdot}0305 & (3)\ k = {\cdot}0150 \\ (4)\ K = {\cdot}0307 & (4)\ k = {\cdot}0149 \end{array} \qquad (5)$$

In order to appreciate the degree of accuracy obtained in these experiments, let us transform equation (4) into the following:

$$\frac{v}{\sqrt{s}} - A - K \sec i \, \frac{uv}{\sqrt{s}} = 0;$$

and substitute in its left hand side the values of $K \sec i$ and mean values of A found above. The results of this substitution for the four series of experiments are as follows, in which Φ denotes the left hand side of the equation just given.

FIRST SERIES.

$\Phi =$	1°	+ ·0018
	3°	− ·0050
	4°	+ ·0041
	5°	− ·0048
	6°	− ·0001
	7°	+ ·0011
	8°	+ ·0031

SECOND SERIES.

$\Phi =$	1°	+ ·0008	7°	+ ·0016
	2°	− ·0041	8°	+ ·0038
	3°	− ·0078	9°	+ ·0044
	4°	− ·0064	10°	+ ·0085
	5°	− ·0058	11°	+ ·0032
	6°	− ·0047	12°	+ ·0065

THIRD SERIES.

$\Phi =$	1°	+ ·0023
	2°	− ·0065
	3°	+ ·0014
	4°	+ ·0029

FOURTH SERIES.

$\Phi =$	1°	+ ·0064
	2°	− ·0112
	3°	− ·0040
	4°	+ ·0089

It is evident, on inspection of the foregoing results, that $\Phi = 0$ is true to *two* places of decimals; and it is not difficult to prove, that it may be inferred from this, that the values of K and k (5) are true to *three* places of decimals.

From the remarkable agreement of all these results, I think we are entitled to assume, that equation (4), or its equivalent $\Phi = 0$, is fully established.

In order to determine the lowest velocities for which equation (4) might be considered proved, I added to the third and fourth series of experiments a set of experiments, the object of which was to ascertain the point from which the waggon should be allowed to descend, so as just to move the Friction Sledge. The result of these trials was as follows:

	v'.	$\sqrt{s}$.	v.	u.	$\frac{v}{\sqrt{s}}$	$\frac{uv}{\sqrt{s}}$
Third day,	3·240	·142	3·078	31·88	21·6760	691·0308
Fourth day,	3·205	·110	2·885	31·99	26·2273	839·0017

Substituting these expressions in equation (4), and replacing A by ·1681 and ·1491 on the third and fourth days respectively, we obtain

$$K = \cdot 0311, \qquad K = \cdot 0310.$$

The agreement of these results with (5) is sufficient to prove, that the equation from which they are deduced is true for velocities as low as 3 feet per second.

The experimental truth of equation (4) being thus established, the results obtained from the foregoing series of experiments may be briefly summed up as follows:

1st. The momentum possessed by the waggon at the moment of impact on the Sledge is destroyed by two causes, which may be considered separately: first, the loss of momentum occasioned by the shock itself, and the adhesion of the Sledge to the rails; this I have called the *Friction of Rest:* secondly, the loss of momentum which takes place after the Sledge is set in motion, caused by friction against the rails; this is the *Friction of Motion.*

2nd. The friction of rest is directly proportional to the pressure against the rails, and to the velocity of impact, jointly.

3rd. The friction of motion is directly proportional to the pressure against the rails, and is independent of the velocity.